Global CO2 simulations and the impacts of cloud convection on atmospheric CO2 distributions

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Acknowledge:

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Phil Rasch (NCAR)

Shiliang Wu (Harvard)

Objectives

- Explore on what extent the convection schemes impact on atmospheric CO_2 distribution

  (three referred cloud convection schemes are used to test their impacts on the atmospheric CO_2 distributions.)

- Examine the sensitivity of atmospheric CO_2 to its regional emission/sink

  (three emission scenarios are constructed constrained by IPCC 2001 framework to examine their impacts on the atmospheric CO_2 under a 'fixed' convection.)

‘Standard’ simulation

_ Simulate global CO2 at year 2000 with Unified Chemistry Transport Model (UCTM) by repeating Kawa’s work (2004);

_ Obtain concurrent CO2 observations from CMDL surface and CMDL aircraft database to evaluate the simulations;

UCTM setting for ‘standard’ simulation:

♦ Spatial resolution: 2º (latitude) x 2.5º (longitude) x 25 eta layers

♦ Temporal resolution: 15 minutes for dynamical processes

♦ Driven by GEOS-4 version 3 3-hour assimilated meteorological fields

♦ Same transport algorithms as in PCTM [Kawa et al., 2004], convection code denoted as CONV1

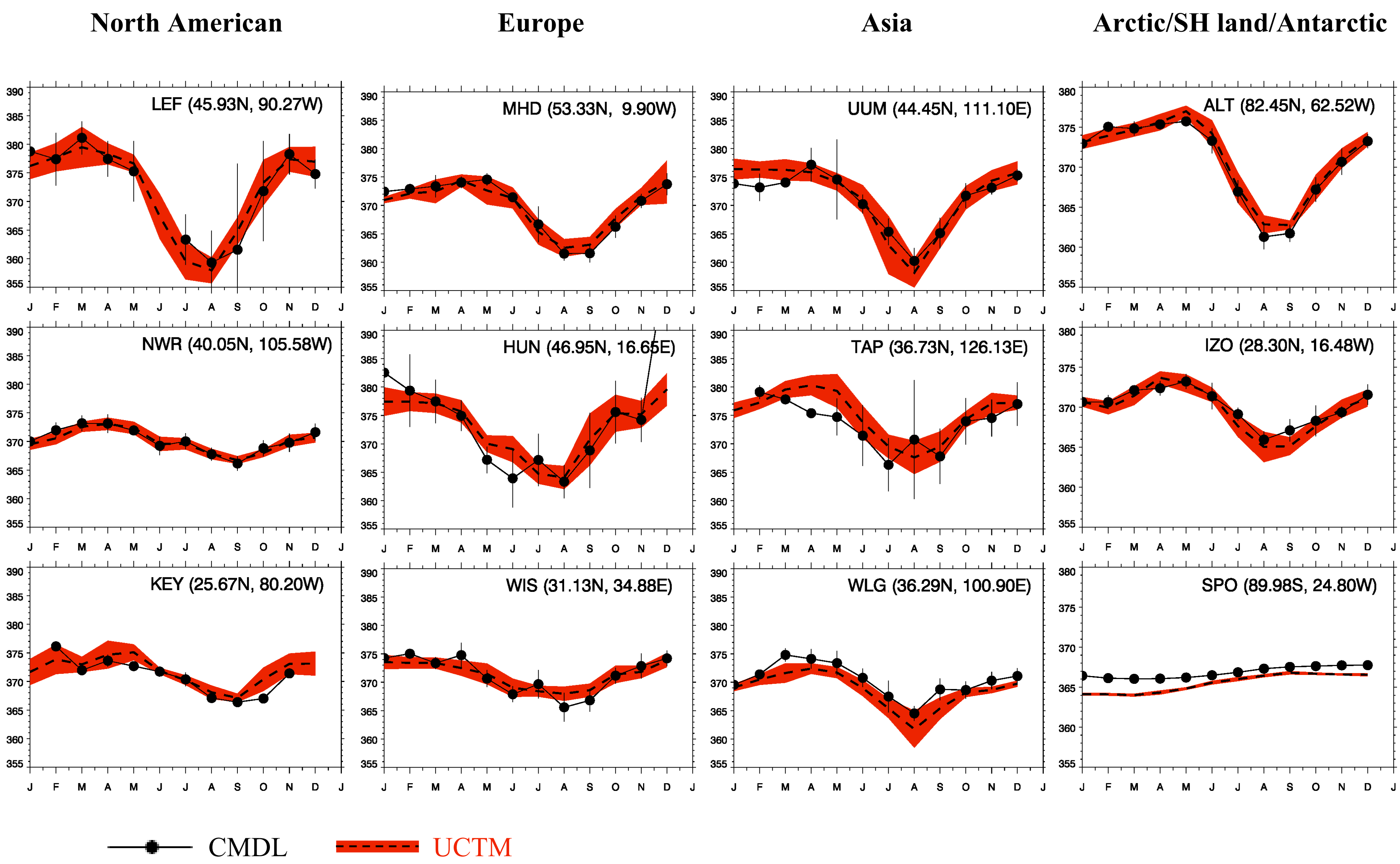
♦ A ‘background’ emission scenario (Emi.1) from TransCom3

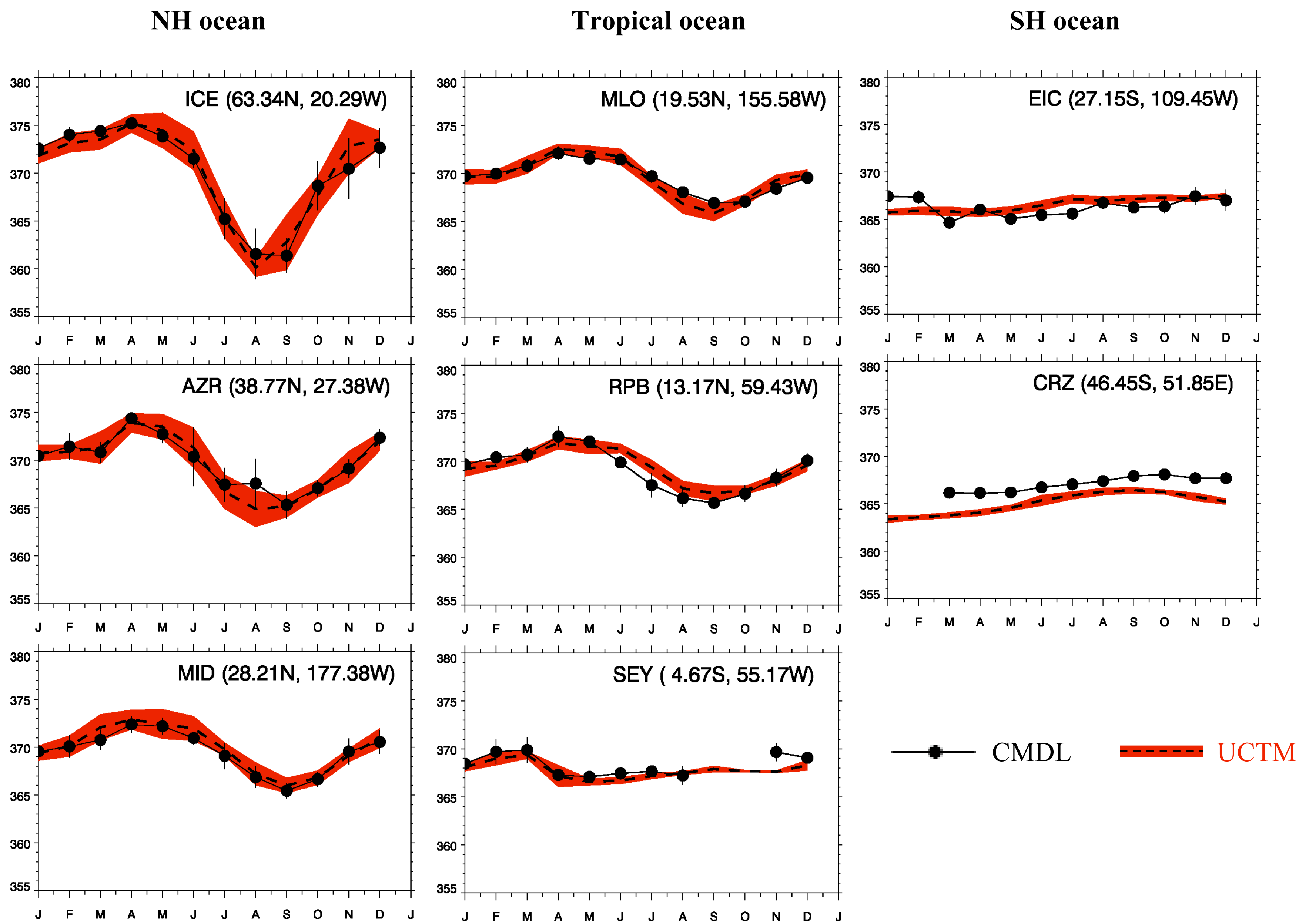
Features of model and observations

	Spatial resolution	Temporal resolution
Model	2º x 2.5º	daily average
CMDL surface	on site	instantaneously, weekly sample
CMDL aircraft	on site	instantaneously, usually afternoon, 0-2 samples /month

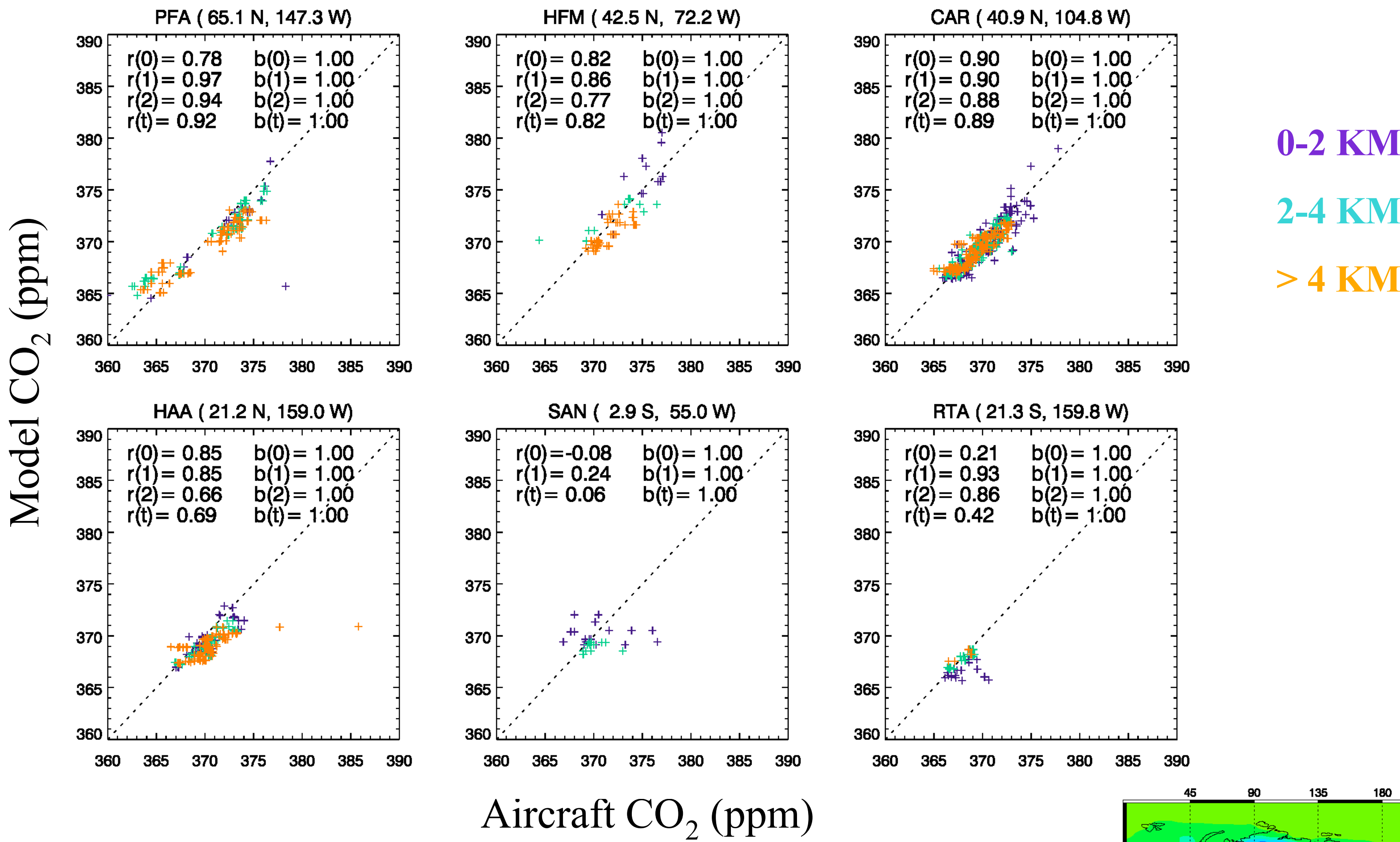
Representation error

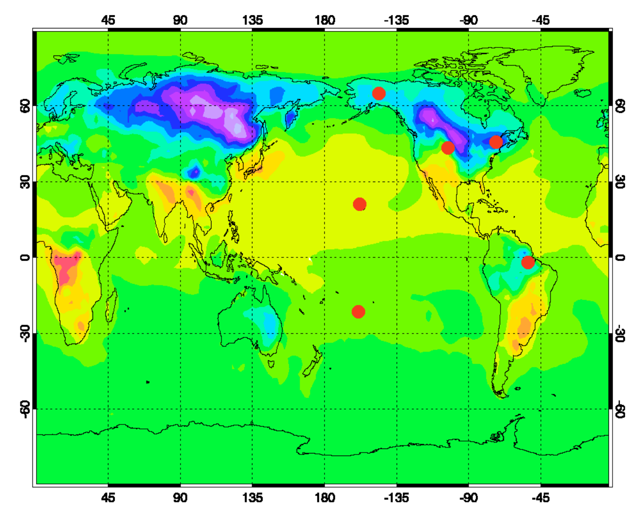
Rectification error


North American
Europe
Asia
Arctic/SH land/Antarctic
LEF (45.93N, 90.27W)
MHD (53.33N, 9.90W)
UUM (44.45N, 111.10E)
ALT (82.45N, 62.52W)
NWR (40.05N, 105.58W)
HUN (46.95N, 16.65E)
TAP (36.73N, 126.13E)
IZO (28.30N, 16.48W)
KEY (25.67N, 80.20W)
WIS (31.13N, 34.88E)
WLG (36.29N, 100.90E)
SPO (89.98S, 24.80W)
J F M A M J J A S O N D J
CMDL
UCTM

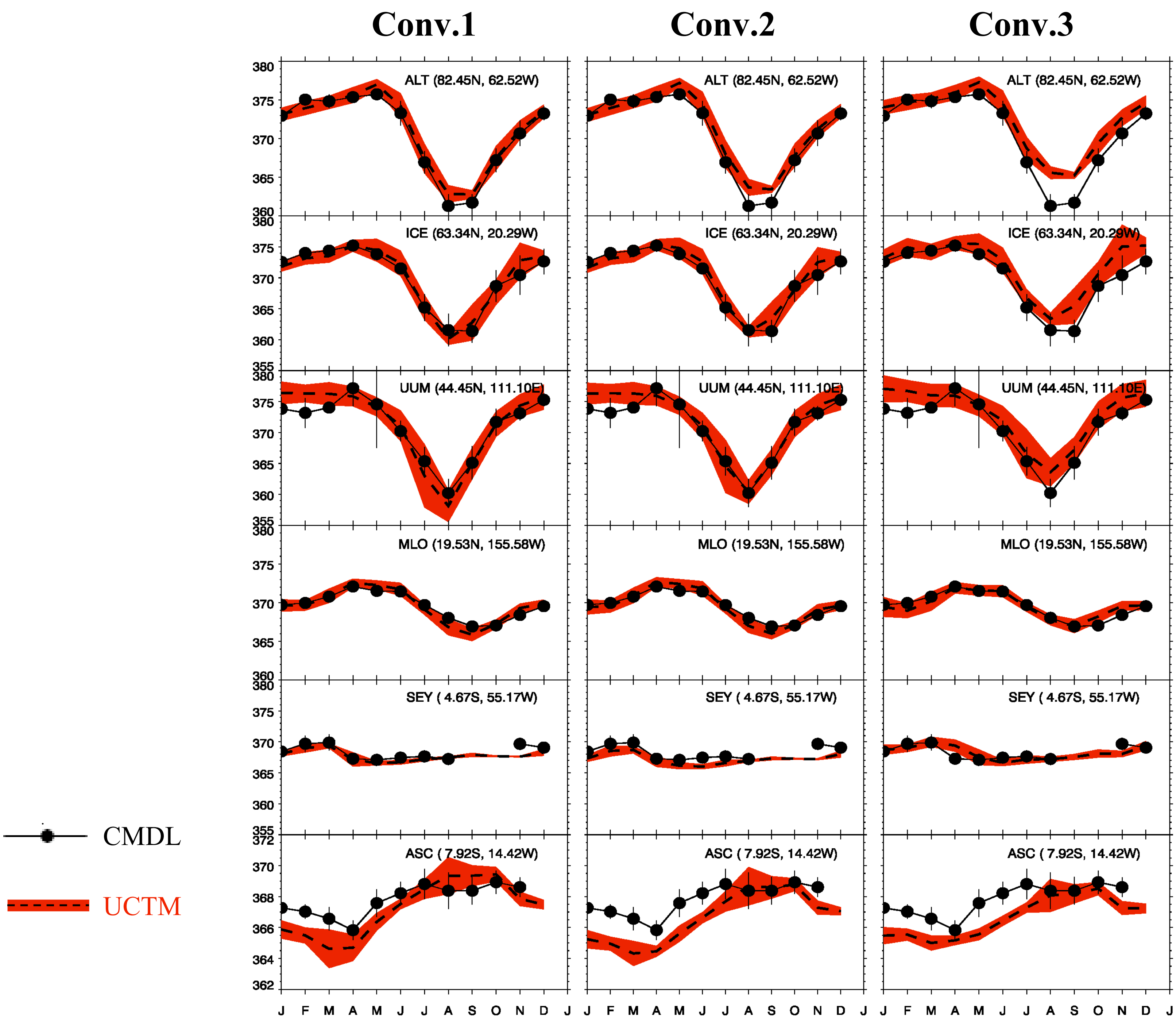


NH ocean
Tropical ocean
SH ocean
ICE (63.34N, 20.29W)
MLO (19.53N, 155.58W)
EIC (27.15S, 109.45W)
AZR (38.77N, 27.38W)
RPB (13.17N, 59.43W)
CRZ (46.45S, 51.85E)
MID (28.21N, 177.38W)
SEY (4.67S, 55.17W)
380
375
370
365
360
355
J F M A M J J A S O N D J
CMDL
UCTM

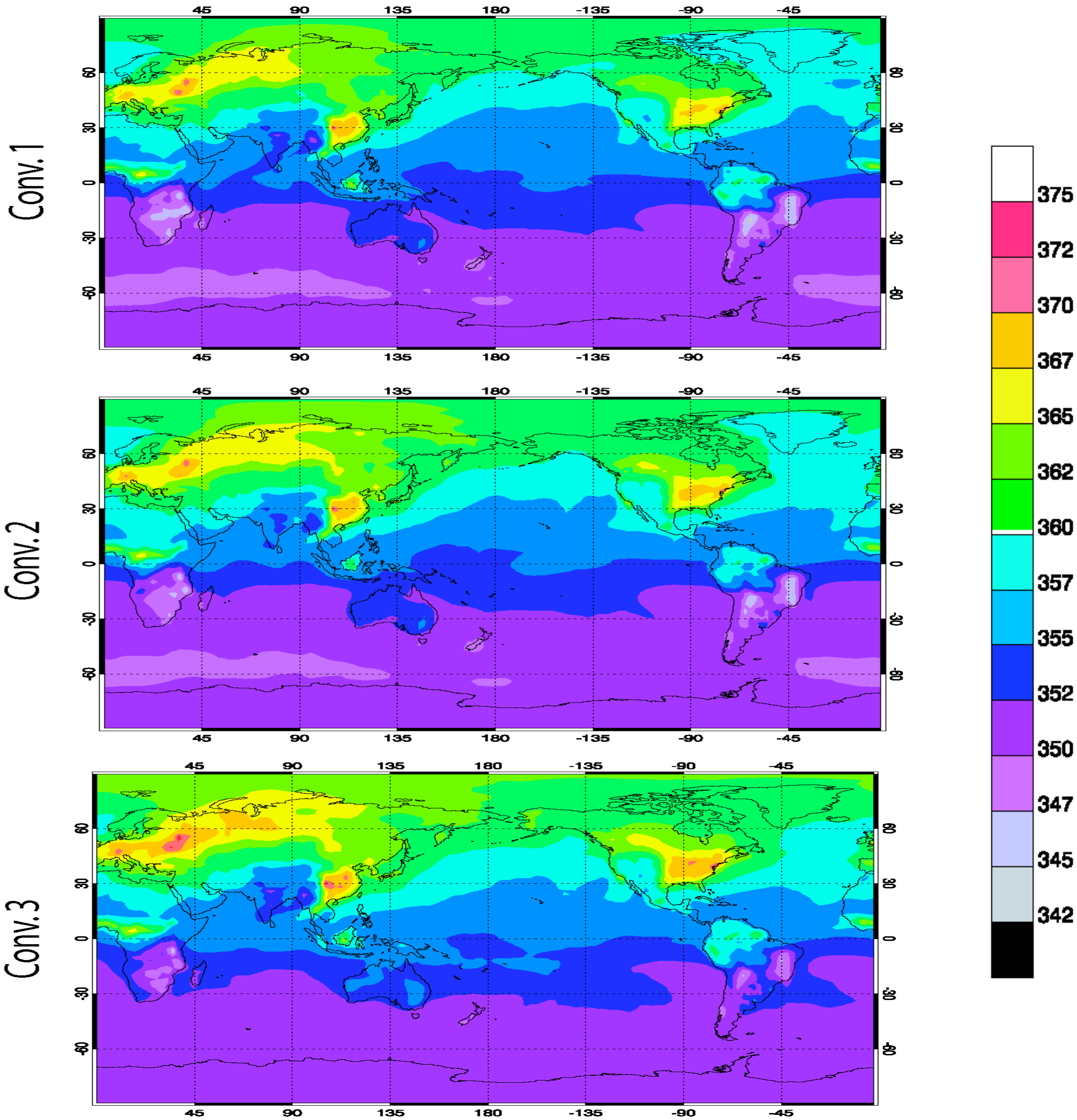

PFA (65.1 N, 147.3 W)
r(0)= 0.78 b(0)= 1.00
r(1)= 0.97 b(1)= 1.00
r(2)= 0.94 b(2)= 1.00
r(t)= 0.92 b(t)= 1.00
HFM (42.5 N, 72.2 W)
r(0)= 0.82 b(0)= 1.00
r(1)= 0.86 b(1)= 1.00
r(2)= 0.77 b(2)= 1.00
r(t)= 0.82 b(t)= 1.00
CAR (40.9 N, 104.8 W)
r(0)= 0.90 b(0)= 1.00
r(1)= 0.90 b(1)= 1.00
r(2)= 0.88 b(2)= 1.00
r(t)= 0.89 b(t)= 1.00
HAA (21.2 N, 159.0 W)
r(0)= 0.85 b(0)= 1.00
r(1)= 0.85 b(1)= 1.00
r(2)= 0.66 b(2)= 1.00
r(t)= 0.69 b(t)= 1.00
SAN (2.9 S, 55.0 W)
r(0)=-0.08 b(0)= 1.00
r(1)= 0.24 b(1)= 1.00
r(t)= 0.06 b(t)= 1.00
RTA (21.3 S, 159.8 W)
r(0)= 0.21 b(0)= 1.00
r(1)= 0.93 b(1)= 1.00
r(2)= 0.86 b(2)= 1.00
r(t)= 0.42 b(t)= 1.00
360 365 370 375 380 385 390
Model CO2 (ppm)
Aircraft CO2 (ppm)
0-2 KM
2-4 KM
> 4 KM


45 90 135 180 -135 -90 -45
60 30 0 -30 -60

	Conv1	Conv2	Conv3
References	Kawa 2004	Lin 1996	Hack 1994; Zhang & McFarlane 1995
Implemented in	PCTM	GOCART; GOES-CHEM	MATCH; GOES-CHEM
Differentiate tracer in & out cloud	NO	YES	YES
Numerical scheme	a semi-implicit	an upstream differencing	an upstream differencing
Differentiate shallow & deep cloud	NO	NO	YES
Constrained by	cloud mass flux	cloud mass flux; detrainment; entrainment	shallow: shallow cloud mass; overshot parameter deep: updraft; downdraft; updraft entrainment; updraft detrainment; downdraft entrainment

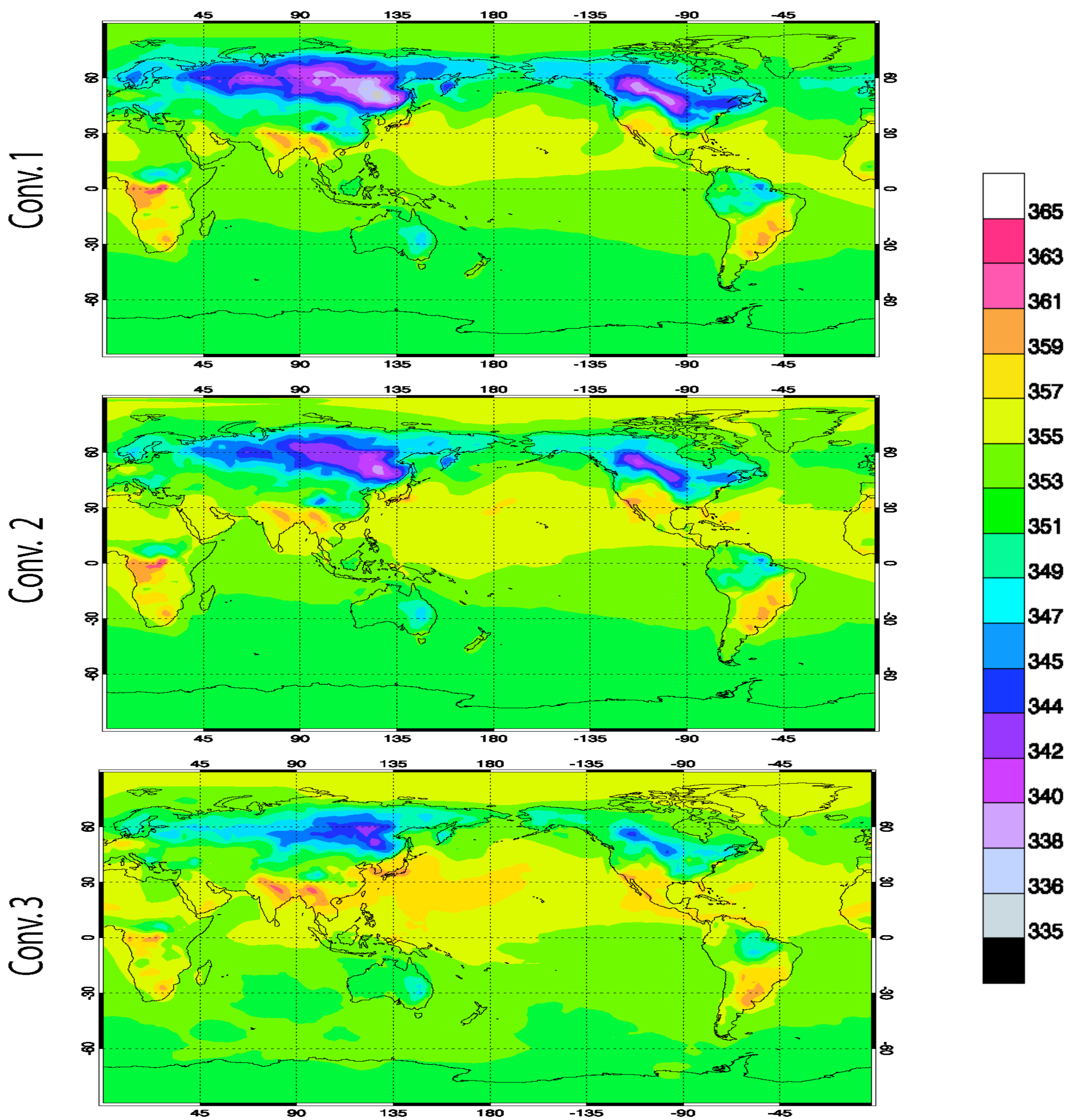

Conv.1
Conv.2
Conv.3
ALT (82.45N, 62.52W)
ICE (63.34N, 20.29W)
UUM (44.45N, 111.10E)
MLO (19.53N, 155.58W)
SEY (4.67S, 55.17W)
ASC (7.92S, 14.42W)
J F M A M J J A S O N D J
CMDL
UCTM

Surface CO2 [ppm], January 2000

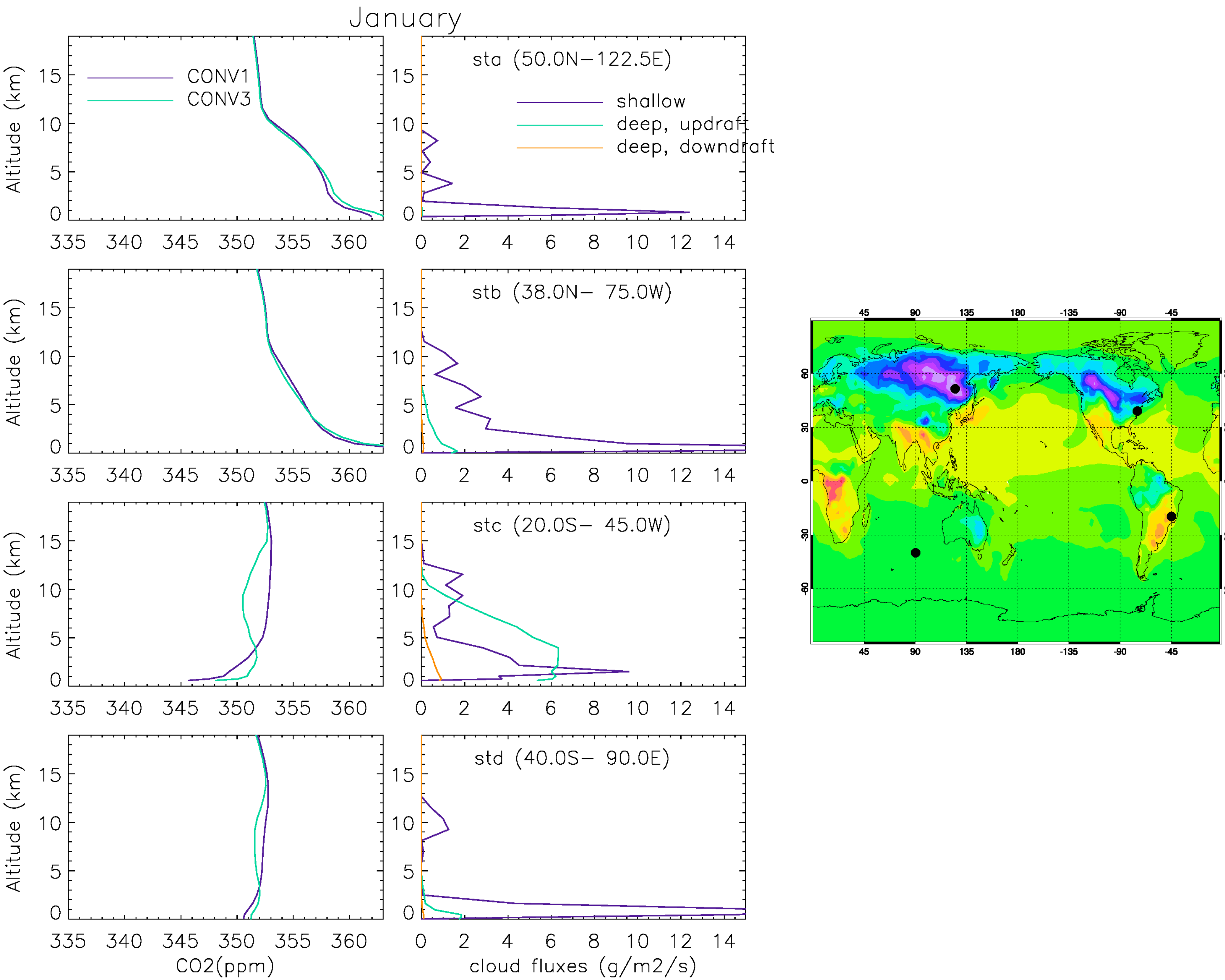


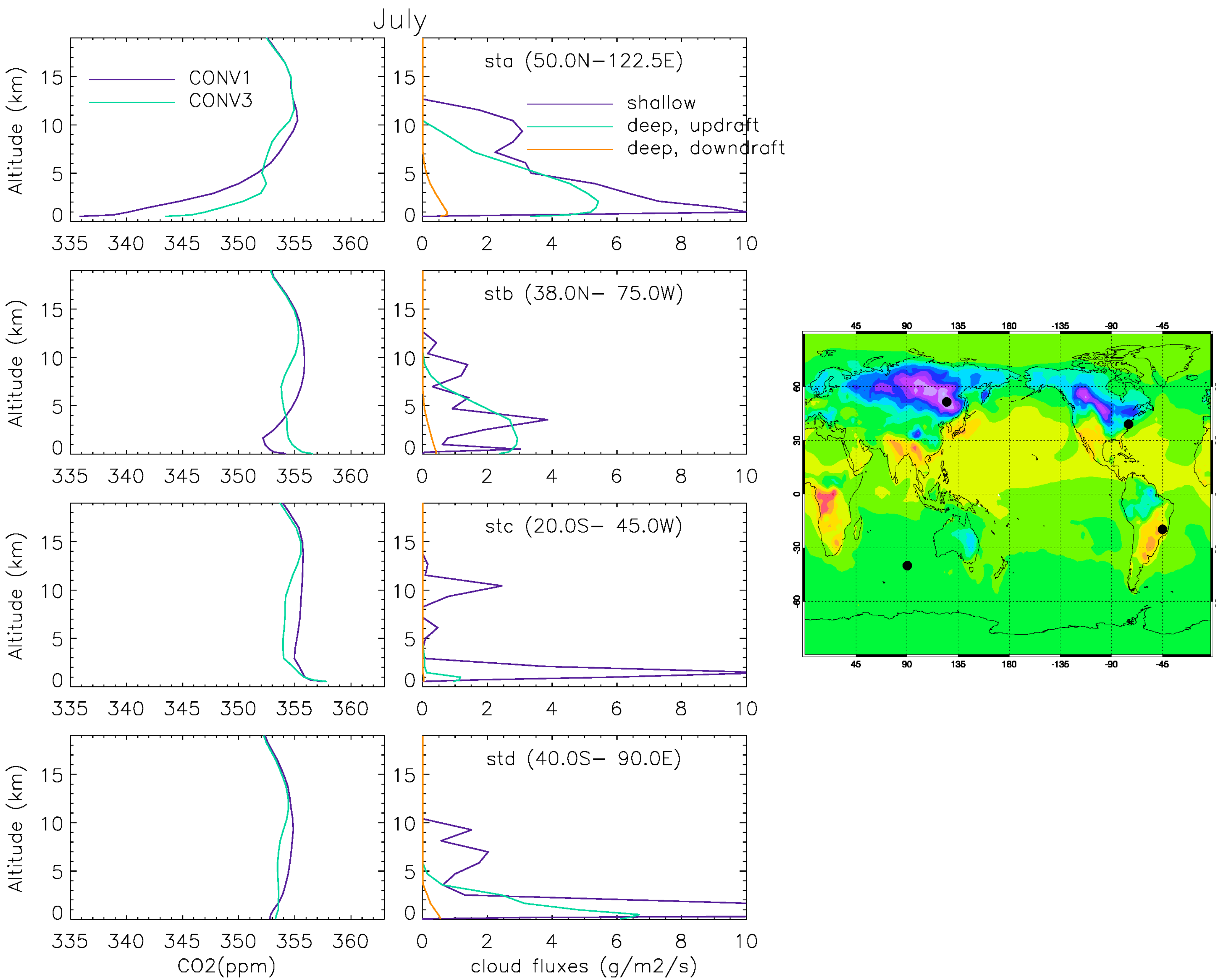
	Max.	Min.
Conv.1	373.3	344.0
Conv.2	373.4	344.8
Conv.3	375.3	346.3

Surface CO_2 [ppm], July 2000

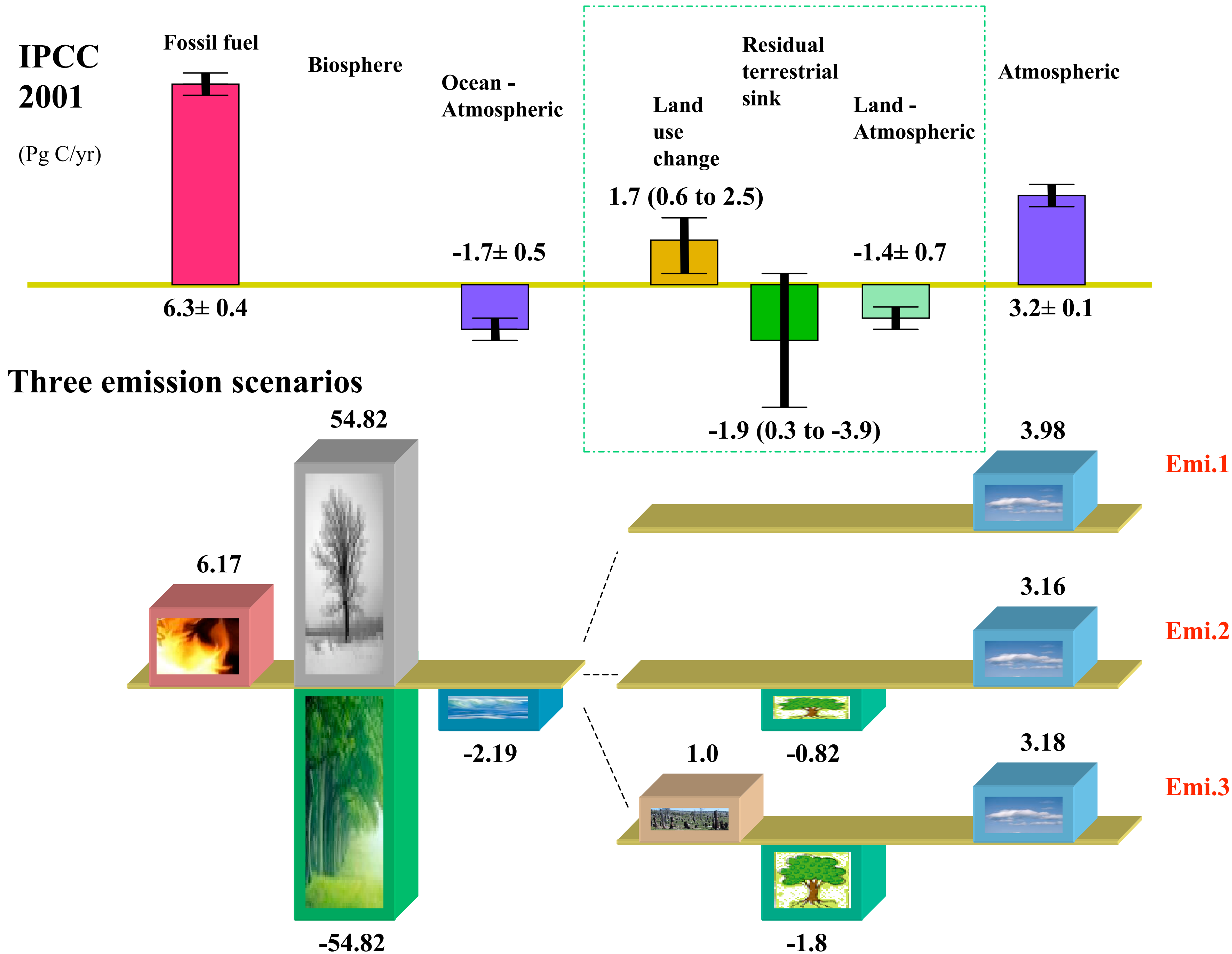


Max.	Min.
363.8	335.4
363.4	339.1
363.1	343.1

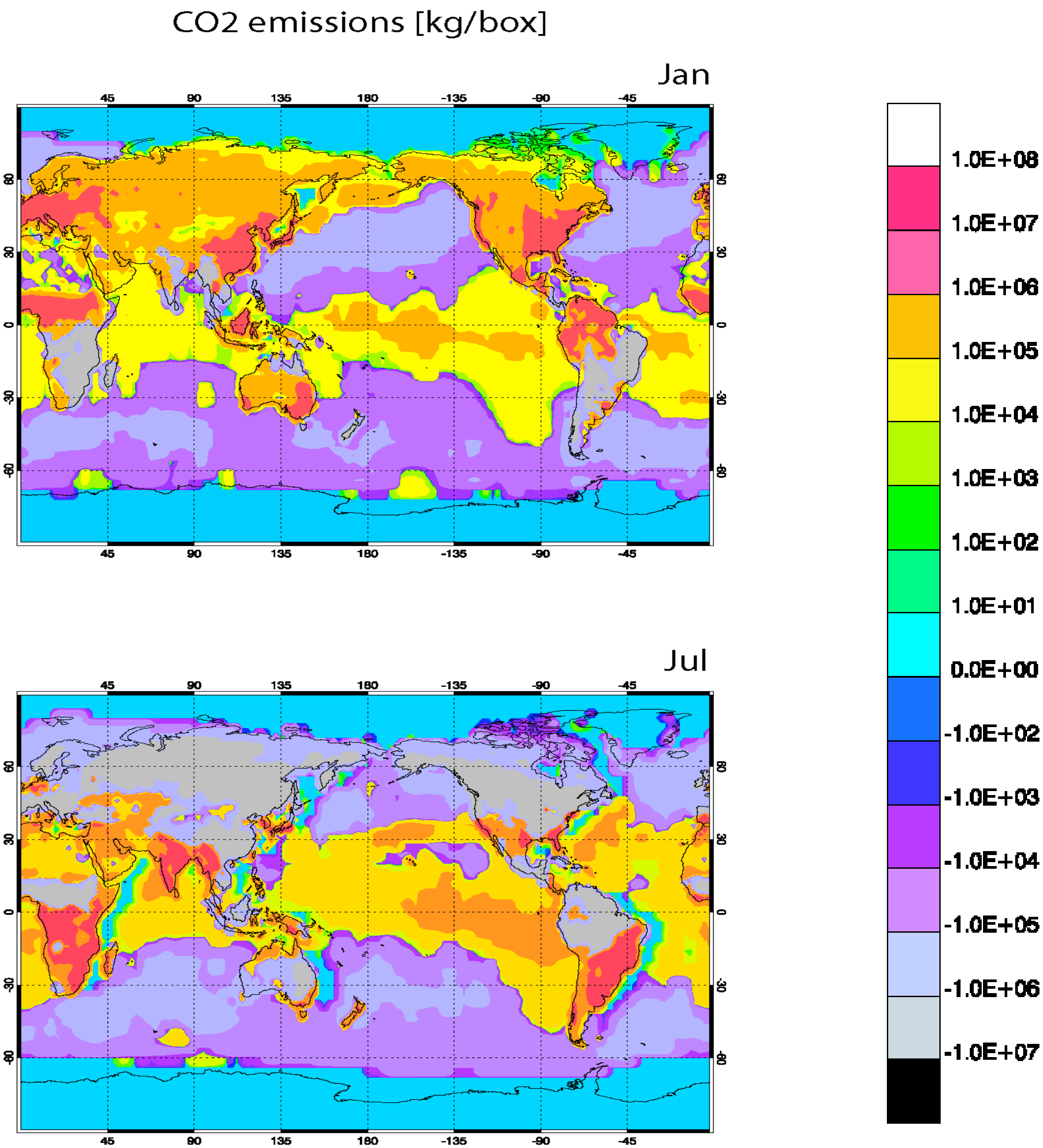

January
CONV1
CONV3
sta (50.0N−122.5E)
shallow
deep, updraft
deep, downdraft
stb (38.0N− 75.0W)
stc (20.0S− 45.0W)
std (40.0S− 90.0E)
Altitude (km)
CO2(ppm)
cloud fluxes (g/m2/s)



July
CONV1
CONV3
Altitude (km)
CO2(ppm)
sta (50.0N–122.5E)
shallow
deep, updraft
deep, downdraft
stb (38.0N– 75.0W)
stc (20.0S– 45.0W)
std (40.0S– 90.0E)
cloud fluxes (g/m2/s)

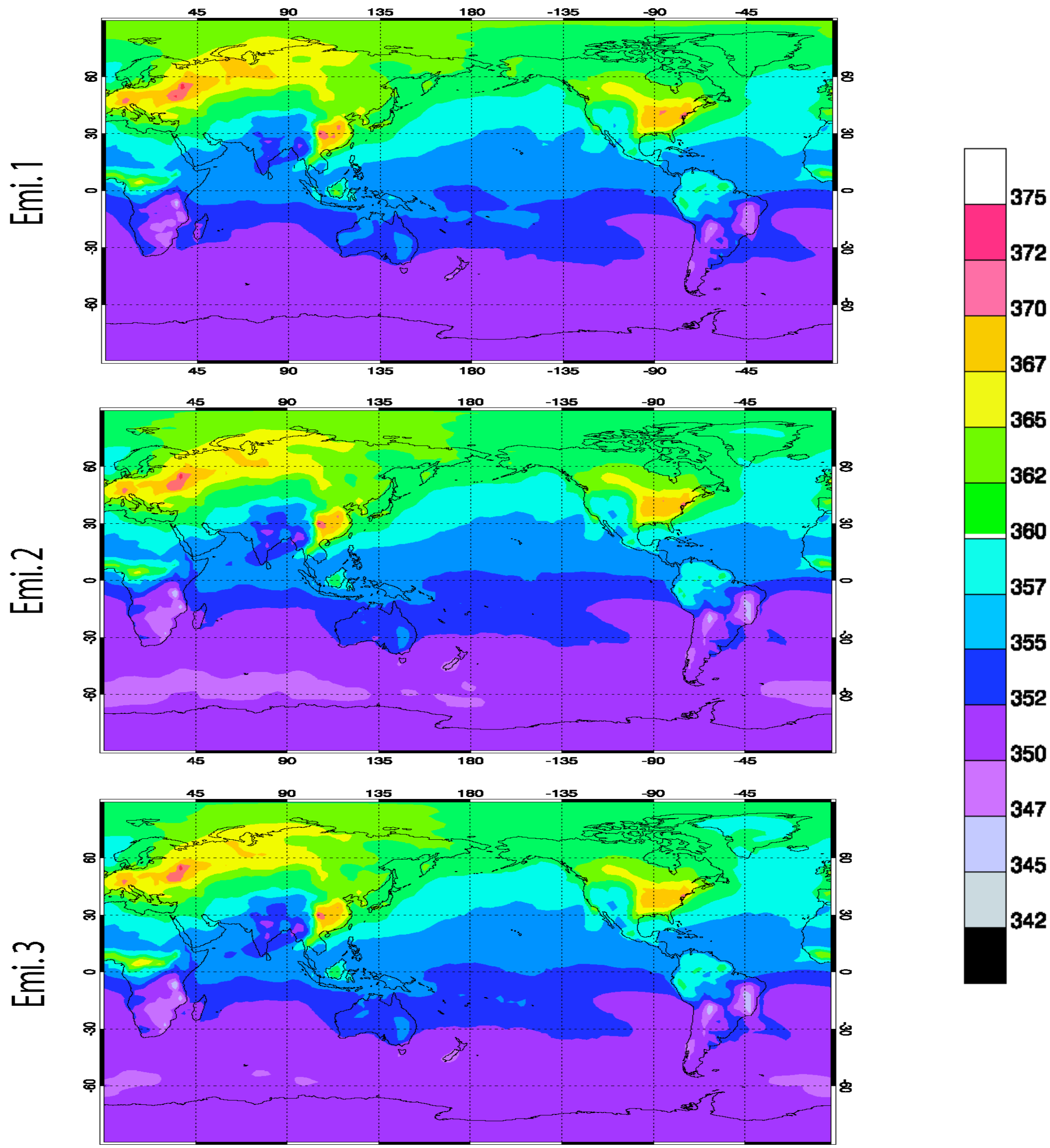

IPCC 2001
(Pg C/yr)
Fossil fuel
Biosphere
Ocean - Atmospheric
Land use change
Residual terrestrial sink
Land - Atmospheric
Atmospheric
6.3± 0.4
-1.7± 0.5
1.7 (0.6 to 2.5)
-1.9 (0.3 to -3.9)
-1.4± 0.7
3.2± 0.1
Three emission scenarios
6.17
54.82
-54.82
-2.19
3.98
Emi.1
3.16
-0.82
Emi.2
1.0
3.18
-1.8
Emi.3

Emi. 1



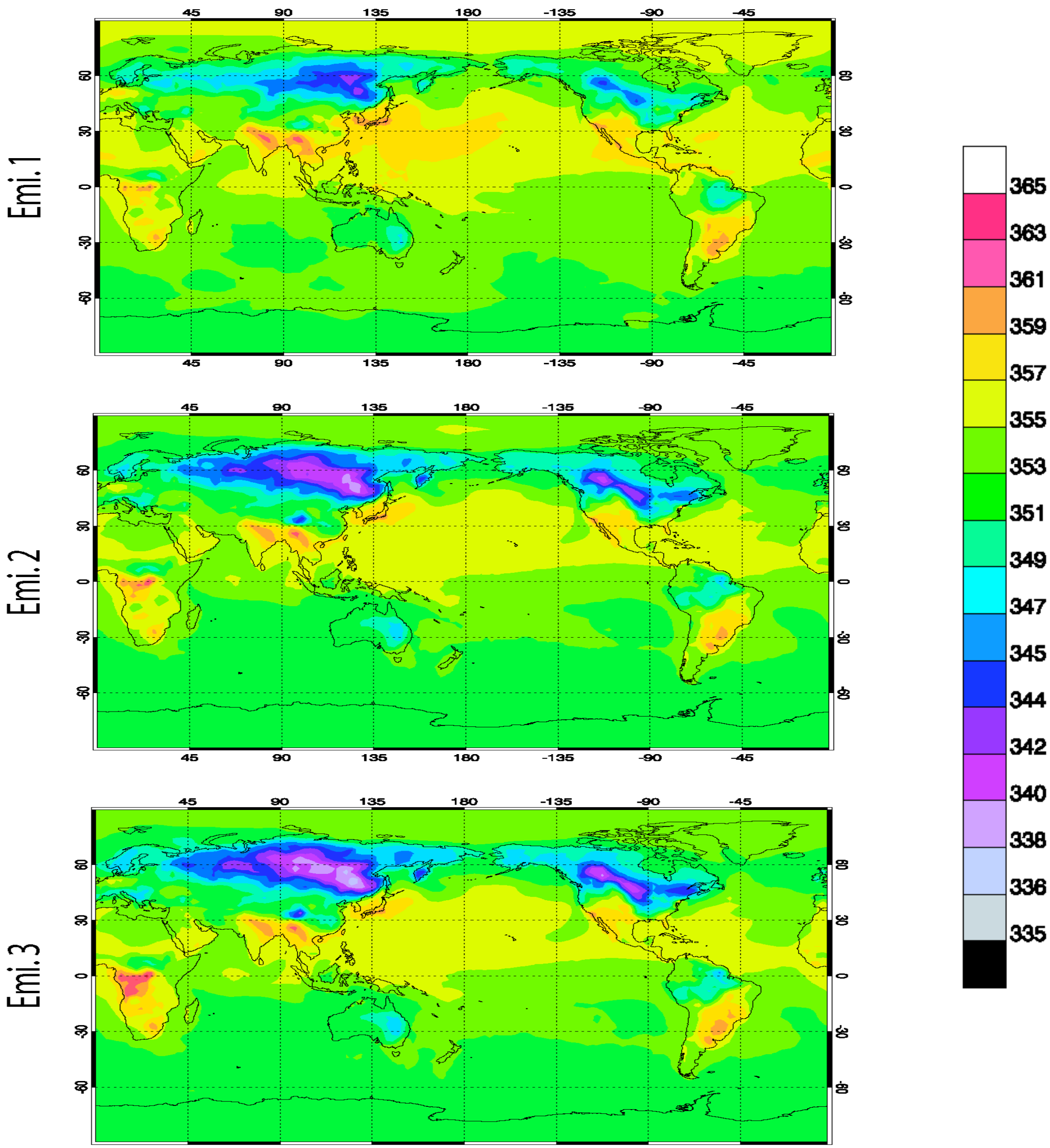
CO2 emissions [kg/box]
Jan
Jul
45
90
135
180
-135
-90
-45
60
30
0
-30
-60
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
0.0E+00
-1.0E+02
-1.0E+03
-1.0E+04
-1.0E+05
-1.0E+06
-1.0E+07

Surface CO2 [ppm], January 2000

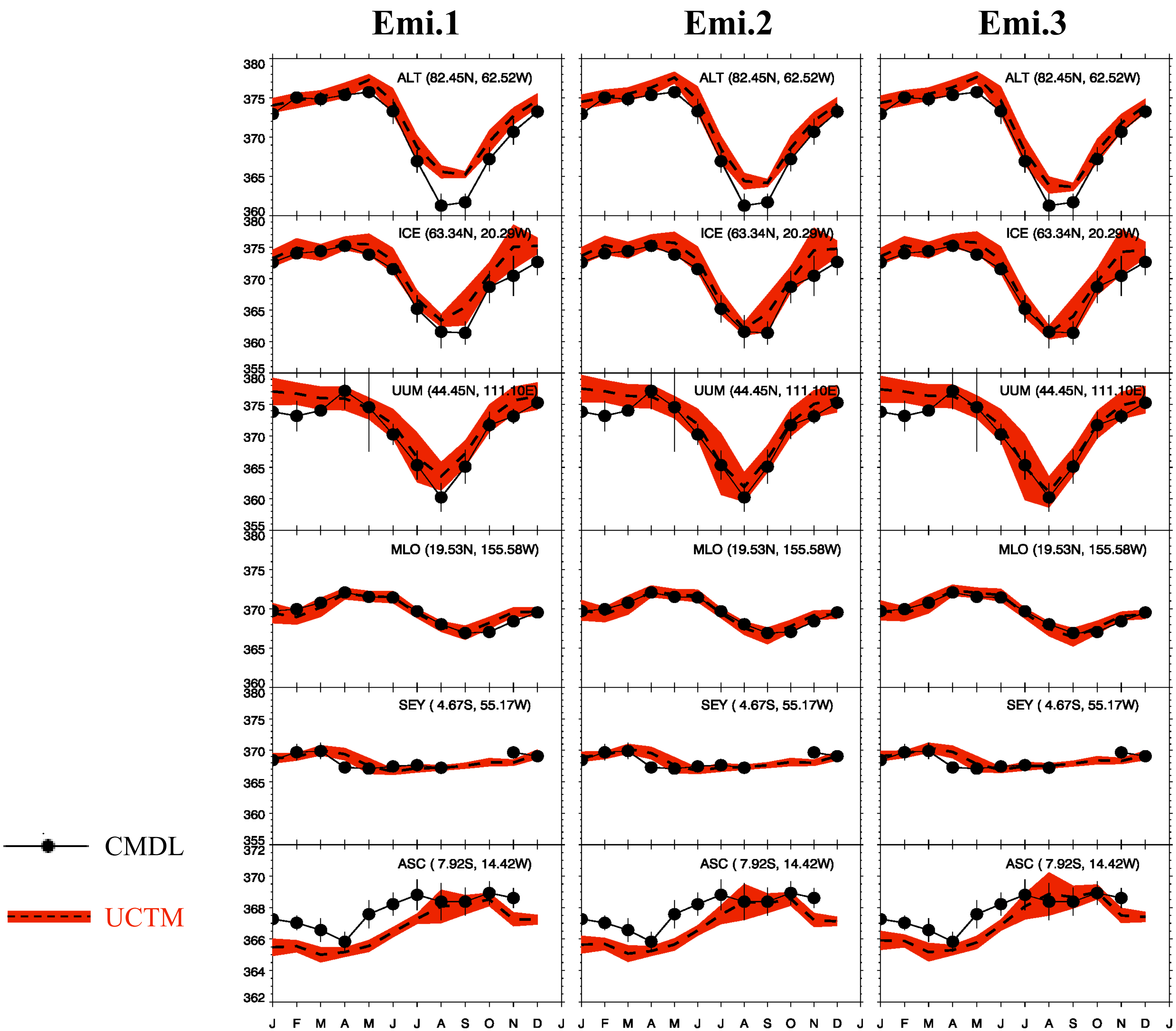


Max.	Min.
375.3	346.3
375.0	345.4
374.9	345.0

Surface CO_2 [ppm], July 2000



Max.	Min.
363.1	343.1
363.4	338.7
364.5	337.2



Emi.1
Emi.2
Emi.3
ALT (82.45N, 62.52W)
ICE (63.34N, 20.29W)
UUM (44.45N, 111.10E)
MLO (19.53N, 155.58W)
SEY (4.67S, 55.17W)
ASC (7.92S, 14.42W)
CMDL
UCTM
J F M A M J J A S O N D J

Summary

- Atmospheric CO discrepancies are apparent by using different convection transport algorithms within a single CTM framework.

- The maximum displacements occur in boreal forest summer season, and it reasonably occurs between CONV1 and CONV3 with a CO_2 difference of 7.7 ppm, which is about a quarter of the CO_2 seasonality for that area.

- This summer largest discrepancy is primarily attributed to the season's severe deep cloud activities which are represented in different ways in three convection approaches.

- The discrepancies shown here serve the low bound of potential convection error in the forward models.

- Differences between the “complete” and “approximate” cloud transport forms have similar magnitude to uncertainties in the emissions, in the context of agreement between simulations and observations.

- A potentially much greater investment for this type of work would be to work on-line in the GCM and develop a convective transport configuration that works well for both meteorology and for trace gases (SF6, radon, CO2, etc)

Approach

_ Simulate global CO2 at year 2000 with Unified Chemistry Transport Model (UCTM) by repeating a “Standard simulation”;

_ Obtain concurrent CO2 observations from CMDL surface and CMDL aircraft database to evaluate the simulations;

_ Apply three referred cloud convection schemes to investigate their impacts on the atmospheric CO2 distributions.

_Construct three emission scenarios constrained by IPCC 2001 framework and examine their impacts on the atmospheric CO2 under a ‘fixed’ convection.

UCTM

- Spatial resolution: 2º (latitude) x 2.5º (longitude) x 25 eta layers
- Temporal resolution: 15 minutes for dynamical processes
- Driven by GEOS-4 version 3 3-hour assimilated meteorological fields
- Processes for CO2 including emissions and transport
- A ‘background’ emission scenario from TransCom3

Impacts of emission uncertainties in CO_2 ecosystem on atmospheric CO_2 distributions

CO2 emissions (Pg C/yr):

	Fossil Fuel	Biosphere NEP1	Biosphere NEP2	Land	RTS	Ocean net	Atmos.
	(Andres et al., 1996)	(Randerson et al., 1997)				(Takahashi et al., 1999)	
Emi. 1	6.17	-13.61	+13.61			-2.19	3.98
Emi. 2	6.17	-13.61	+13.61		-0.82	-2.19	3.16
Emi. 3	6.17	-13.61	+13.61	1.00	-1.8	-2.19	3.18

* *NPE1 covers the regions dominated by NPP and NEP2 dominated by RESP.*

** *Land change contains fire and deforest and distributes as the same as biomass burning.*

*** *RTS stands for residual terrestrial sink and contains extra plant growth and ecosystem uptake. It is assumed to be distributed as the same as NEP1 and the magnitudes to be 0.06 and 0.1324 of NEP1, respectively.*

CO2 Budgets: (unit: Pg C/mon or Pg C /yr):

	Fossil Fuel	Biosphere				Ocean	Atmos.
		NPP	RESP.	NEP1	NEP2	net	
	(Andres et al., 1996)	(Randerson et al., 1997)				(Takahashi et al., 1999)	
Jan.		-3.19	3.83	-0.59	1.23	-0.21	
Feb.		-3.05	3.88	-0.61	1.44	-0.17	
Mar.		-3.53	4.09	-0.72	1.28	-0.20	
Apr.		-3.76	4.42	-0.65	1.31	-0.20	
May		-5.20	4.80	-1.19	0.80	-0.20	
Jun.		-6.73	5.13	-2.19	0.59	-0.18	
Jul.		-7.38	5.39	-2.72	0.73	-0.13	
Aug.		-6.42	5.41	-1.98	0.97	-0.13	
Sept.		-4.67	5.15	-0.94	1.42	-0.14	
Oct.		-3.99	4.67	-0.78	1.47	-0.19	
Nov.		-3.55	4.17	-0.62	1.24	-0.21	
Dec.		-3.36	3.89	-0.61	1.14	-0.24	
Ann.	**6.17**	**-54.82**	**+54.82**	**-13.61**	**13.61**	**-2.19**	**3.98**

∗*NEP=NPP-RESP.*

∗*NEP1 covers the regions dominated by NPP and NEP2 dominated by RESP.*

Cloud convection algorithm (Conv.1)

A semi-implicit convective module, constrained by the subgrid-scale cloud mass flux from the assimilation system (Kawa et al, 2004)

Vertical cloud transport is calculated by:

$$q_k^{t+\Delta t} - q_k^t = \frac{g\Delta t}{\Delta p_k}\left[C_{k+1}\left(q_{k+1} - q_k\right) - C_k\left(q_k - q_{k-1}\right)\right]^{t+\Delta t/2}$$

q : is the tracer concentration,

C_k, C_{k+1}: are the net convective mass flux at the upper and lower edges of layer *k*,

t : is the model time step,

$\Delta p_k / g$: is the air mass of the layer.

Cloud convection algorithm (Conv.2)

An upwind differencing scheme derived from the steady state mass continuity of the background air and the cloud air in a vertically discretized flux-form transport equation, constrained by the subgrid-scale cloud mass flux (C) and detrainment (D) from the assimilation system (Lin, 1996)

Vertical cloud transport is calculated by:

$$M_k q_k^{t+1} = M_k q_k^t + \Delta t \left\{ C_{k+1} \left[Q_{k+1}^* - q_k^t \right] - C_k \left[Q_k^* - q_{k-1}^t \right] \right\}$$

$$M_{km} Q_{km}^* = M_{km} q_{km}^t - \Delta t \; C_{km} \left[Q_{km}^* - q_{km-1}^t \right]$$

$$\left(C_k + D_k \right) Q_k^* = E_k q_k^t + C_{k+1} Q_{k+1}^*$$

$$E_k = \left(C_k + D_k \right) - C_{k+1}$$

q_k, q_{k+1}, q_{km} : are the tracer mixing ratios at layer k, k+1, and cloud base,

Q_k^* : is the tracer mixing ratio inside the cloud,

$M_k = 100 \;\; \Delta p_k / g$: is the background air mass per unit area [kg/m^2],

t : is the model time step,

E : the rate of entrainment.

Cloud convection algorithm (Conv.3)

The scheme considers shallow (Hack) convection and deep (Z-M) convection (used in NCAR MATCH transport model and Harvard GEOS-CHEM model).

Shallow convection uses cloud mass fluxes and overshot parameters in a characteristic convective adjustment time scale from the Hack scheme to mix the passive constituents.

Deep convection distinguishes the mass fluxes from updraft, downdraft, updraft entrainment, updraft detrainment, and downdraft entrainment.

Cloud convection algorithm (Cont.)

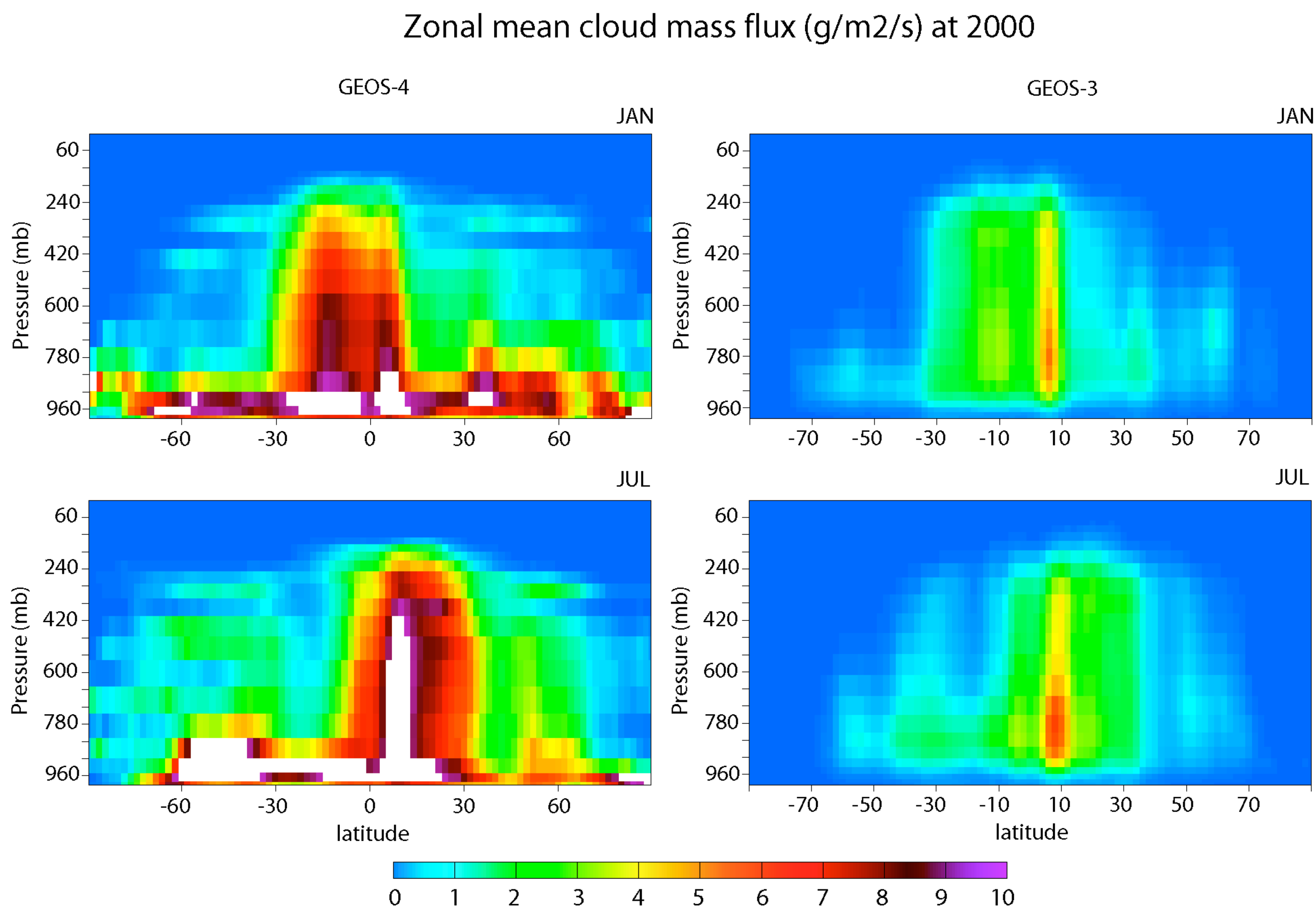
Deep convection uses simple first order upstream biases finite differences to solve the steady state mass continuity equations for the ‘bulk’ updraft and downdraft mixing ratios and the mass continuity equation for the gridbox mean [Collins et al., 2004]

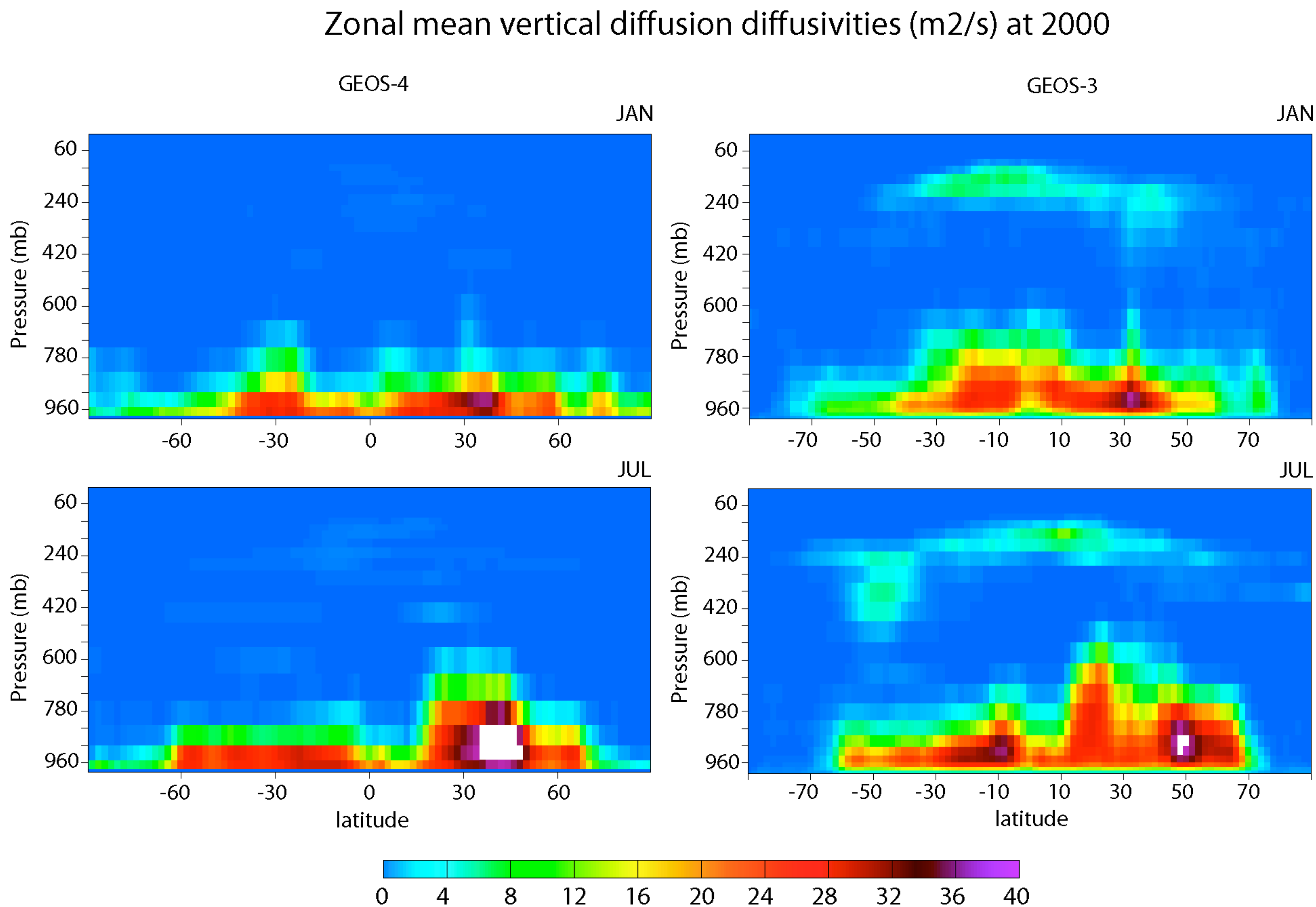
$$\frac{\partial (M_x q_x)}{\partial p} = E_x q_e - D_x q_x$$

$$\frac{\partial \bar{q}}{\partial t} = \frac{\partial}{\partial p}\left(M_u \left(q_u - \bar{q} \right) + M_d \left(q_d - \bar{q} \right) \right)$$

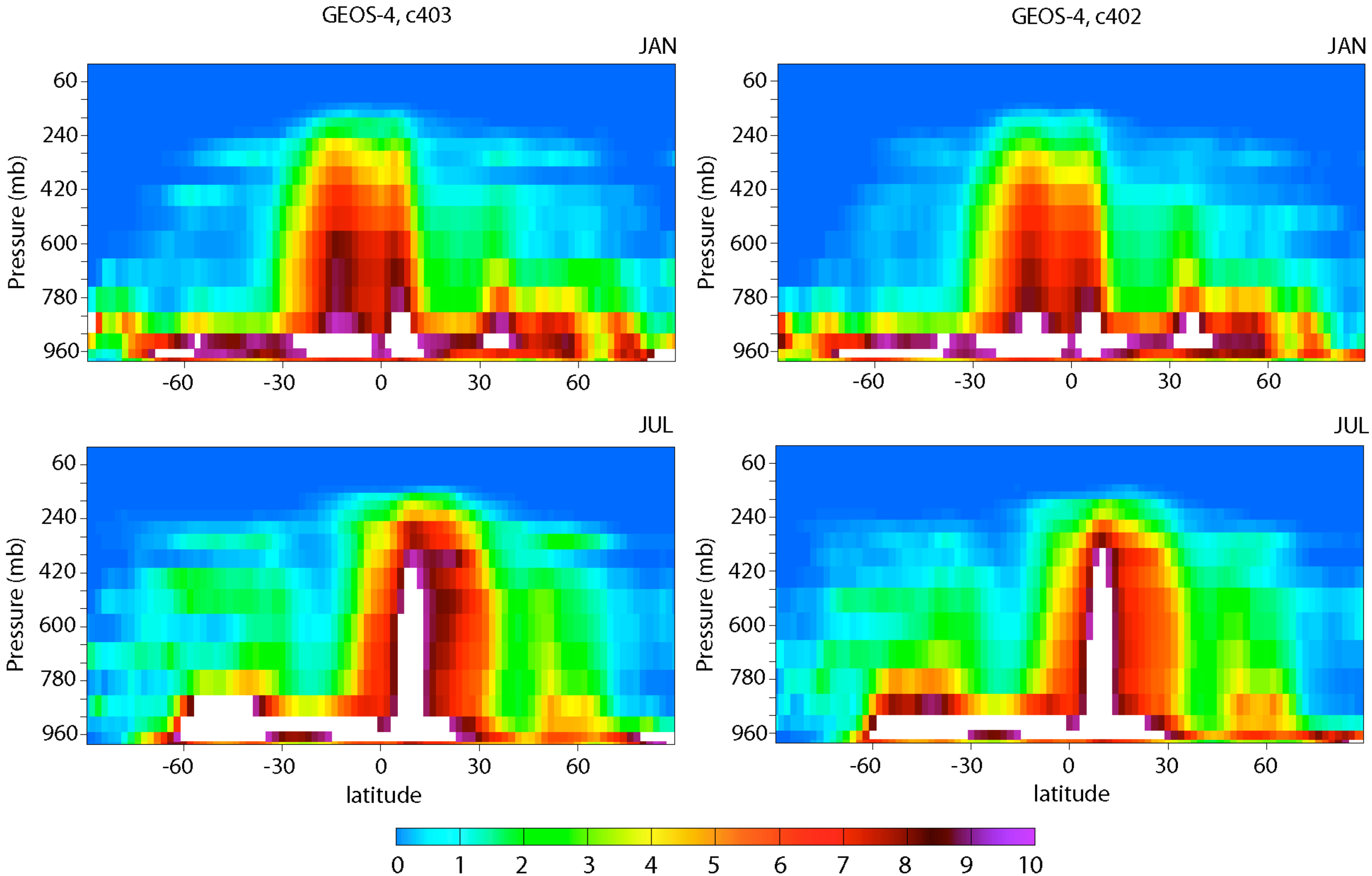
Here subscript x is used to denote the updraft (u) or downdraft (d) quantity. M is the mass flux in units of Pa/s defined at the layer interfaces, q_x is the mixing ratio of the updraft or downdraft. Q_e is the mixing ratio of the quantity in the environment (that part of the grid volume not occupied by the up and downdrafts), and is assumed to be the same as the gridbox averaged mixing ratio . E_x and D_x are the entrainment and detrainment rates (units of s^{-1}) for the up- and down-drafts. Updrafts are allowed to entrain or detrain in any layer. Downdrafts are assumed to entrain only, and all of the mass is assumed to be deposited into the surface layer.

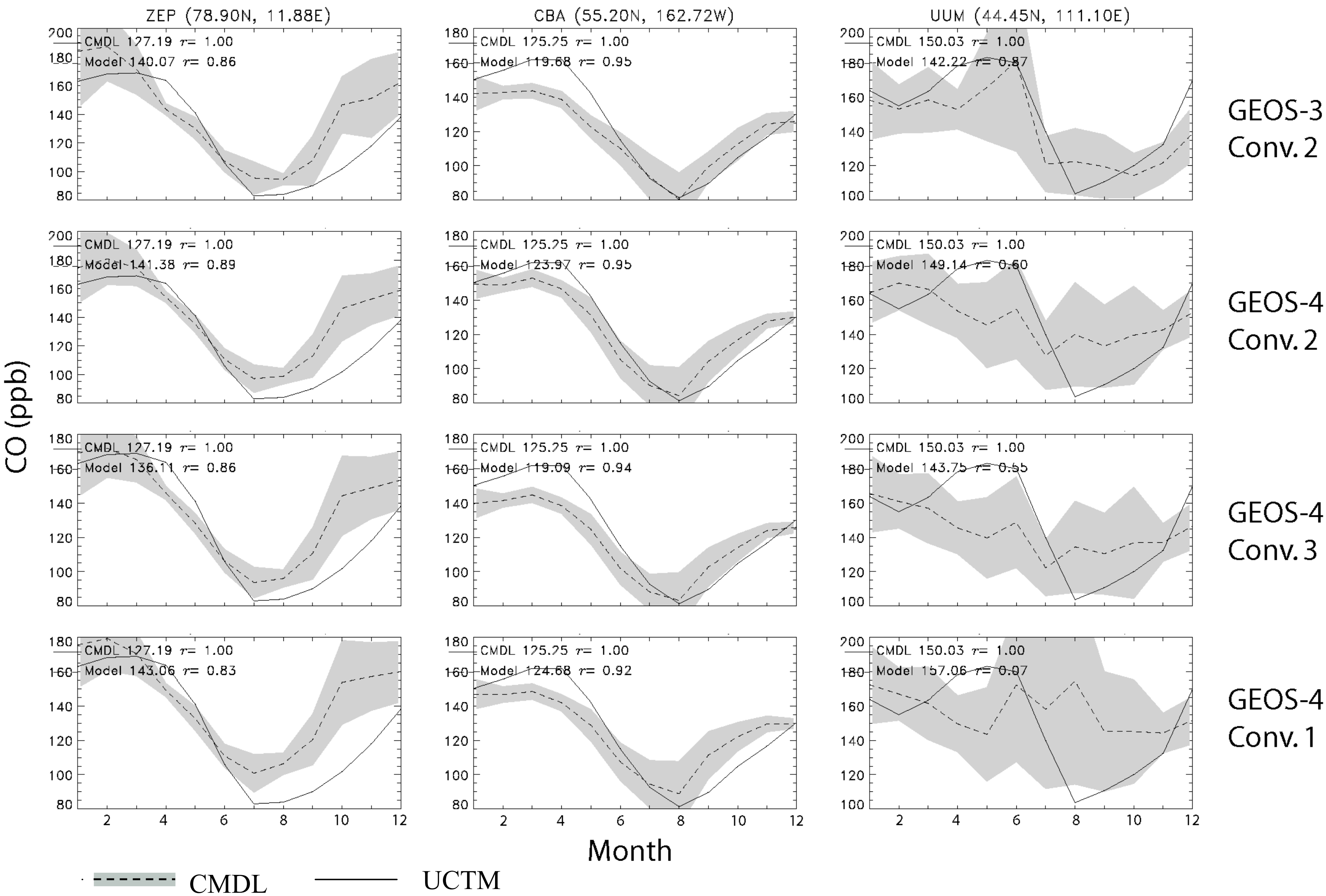
What are the differences of transport fields between GEOS-4 and GEOS-3


Zonal mean cloud mass flux (g/m2/s) at 2000
GEOS-4
GEOS-3
JAN
JUL
Pressure (mb)
60
240
420
600
780
960
-60
-30
0
30
60
-70
-50
-30
-10
10
30
50
70
latitude
0
1
2
3
4
5
6
7
8
9
10

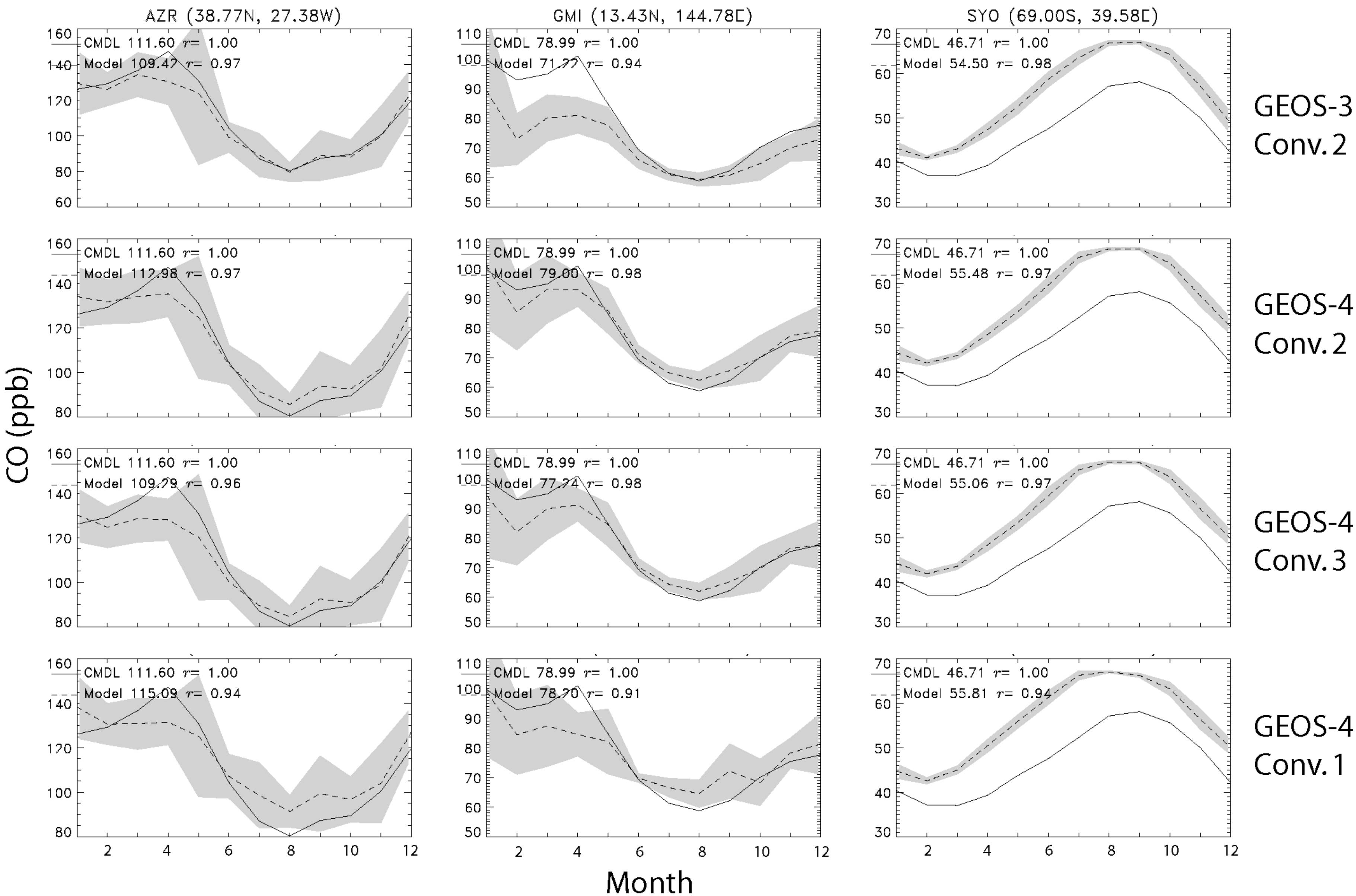

Zonal mean vertical diffusion diffusivities (m2/s) at 2000
GEOS-4
GEOS-3
JAN
JUL
Pressure (mb)
60
240
420
600
780
960
-60
-30
0
30
60
-70
-50
-30
-10
10
30
50
70
latitude
0
4
8
12
16
20
24
28
32
36
40

Zonal mean cloud mass flux (g/m2/s) at 2000

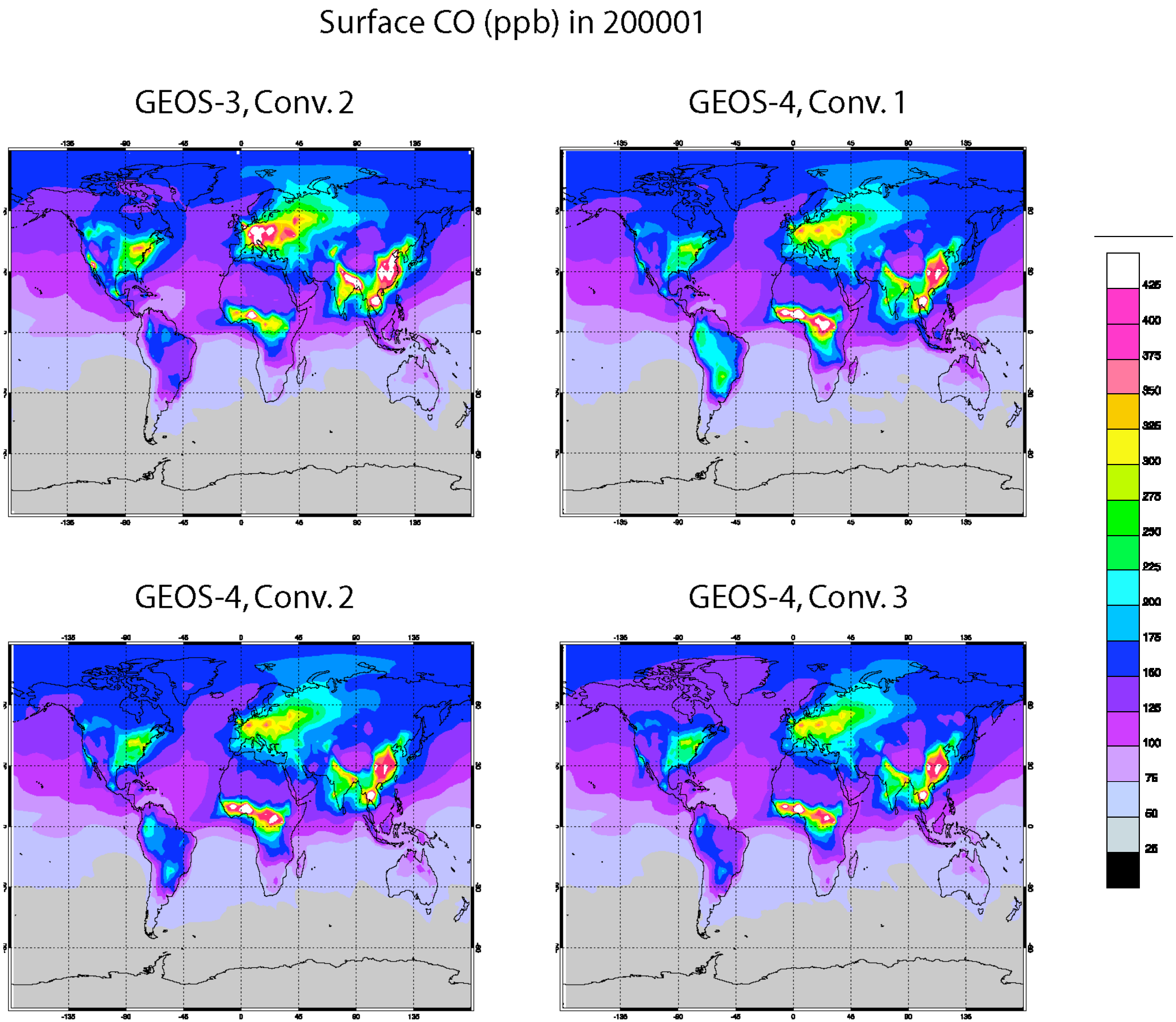




ZEP (78.90N, 11.88E)
CBA (55.20N, 162.72W)
UUM (44.45N, 111.10E)
CMDL 127.19 r= 1.00
Model 140.07 r= 0.86
CMDL 125.25 r= 1.00
Model 119.68 r= 0.95
CMDL 150.03 r= 1.00
Model 142.22 r= 0.87
GEOS-3 Conv. 2
CMDL 127.19 r= 1.00
Model 141.38 r= 0.89
CMDL 125.25 r= 1.00
Model 123.97 r= 0.95
CMDL 150.03 r= 1.00
Model 149.14 r= 0.60
GEOS-4 Conv. 2
CMDL 127.19 r= 1.00
Model 136.11 r= 0.86
CMDL 125.25 r= 1.00
Model 119.09 r= 0.94
CMDL 150.03 r= 1.00
Model 143.75 r= 0.55
GEOS-4 Conv. 3
CMDL 127.19 r= 1.00
Model 143.06 r= 0.83
CMDL 125.25 r= 1.00
Model 124.68 r= 0.92
CMDL 150.03 r= 1.00
Model 157.06 r= 0.07
GEOS-4 Conv. 1
CO (ppb)
Month
CMDL
UCTM



AZR (38.77N, 27.38W)
GMI (13.43N, 144.78E)
SYO (69.00S, 39.58E)
CMDL 111.60 r= 1.00
Model 109.47 r= 0.97
CMDL 78.99 r= 1.00
Model 71.77 r= 0.94
CMDL 46.71 r= 1.00
Model 54.50 r= 0.98
GEOS-3 Conv. 2
CMDL 111.60 r= 1.00
Model 112.98 r= 0.97
CMDL 78.99 r= 1.00
Model 79.00 r= 0.98
CMDL 46.71 r= 1.00
Model 55.48 r= 0.97
GEOS-4 Conv. 2
CMDL 111.60 r= 1.00
Model 109.79 r= 0.96
CMDL 78.99 r= 1.00
Model 77.74 r= 0.98
CMDL 46.71 r= 1.00
Model 55.06 r= 0.97
GEOS-4 Conv. 3
CMDL 111.60 r= 1.00
Model 115.09 r= 0.94
CMDL 78.99 r= 1.00
Model 78.70 r= 0.91
CMDL 46.71 r= 1.00
Model 55.81 r= 0.94
GEOS-4 Conv. 1
CO (ppb)
Month


Surface CO (ppb) in 200001
GEOS-3, Conv. 2
GEOS-4, Conv. 1
GEOS-4, Conv. 2
GEOS-4, Conv. 3
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25

Surface CO (ppb) in 200007